

PROTECTIVE LAYER FOR AN ALUMINUM-CONTAINING ALLOY FOR HIGH-  
TEMPERATURE USE AND METHOD OF PRODUCING SUCH A PROTECTIVE LAYER

CROSS REFERENCE TO RELATED APPLICATIONS

This application is the US national phase of PCT  
application PCT/DE2004/002570, filed 20 November 2004, published 04  
August 2005 as WO2005/071132, and claiming the priority of German  
patent application 102004002946.6 itself filed 21 January 2004,  
whose entire disclosures are herewith incorporated by reference.

FIELD OF THE INVENTION

The invention relates to a protective layer for an  
aluminum-containing alloy for high-temperature use, in particular  
at temperatures up to 1400°C. The invention further relates to a  
method of producing such a protective layer on aluminum-containing  
alloys.

PRIOR ART

Alloys based on Fe-Al, Mi-Al, Ni-Cr-Al or Fe-Cr-Al are  
characterized by an excellent oxidation resistance at very high  
operating temperatures ( $\approx 1400^{\circ}\text{C}$ ). Alloys based on Fe-Al, Mi-Al,  
Ni-Cr-Al or Fe-Cr-Al are characterized by excellent oxidation  
resistance at very high operating temperatures ( $\approx 1400^{\circ}\text{C}$ ). This  
resistance is due to the formation of a thick and slowly growing  
aluminum oxide layer, which forms with high temperature application  
on work surfaces (alloys). This protective cover layer, which is  
caused by selective oxidation of the alloying element aluminum,  
only occurs when the aluminum content in the alloy is sufficiently

large, e.g., at least about 8% by weight in Fe-Al or Ni-Al alloys, and at least about 3% by weight in Fe-Cr-Al or Ni-Cr-Al alloys.

Due to the formation of the cover layer of aluminum oxide, the alloying element present in the aluminum alloy is used up. The use per time unit is generally proportional to the oxide growth rate, and thus increases with increasing temperature, since the oxide growth rate ( $k$  in  $\text{cm}^2$  per second) increases with increasing temperature. The aluminum reservoir present as a whole in an aluminum-containing alloy increases proportionally with the wall thickness of a relevant component. When the component is a layer or foil, the strength typically is proportional to the thickness of the layer, and when the component is a wire, for example to the diameter.

If due to long-term application of a component consisting of an aluminum-containing alloy and the formation of an aluminum oxide layer on its surface, the aluminum content of the alloy is reduced to such an extent that it falls below a critical aluminum concentration, then a further protecting aluminum oxide layer can no longer form. This results in very quick "breakaway oxidation." This time matches the so-called end of life of the components.

It follows from the above considerations that the life of a component declines either with increasing oxide growth rate or decreasing wall thickness.

Some examples of typical remaining-life times ( $t_B$ ) of components consisting of FeCrAl alloys (commercial names, e.g., KANHAL AF or ALUCHROM YHF) varying with the temperature and wall thickness are known from the literature. For instance,

for a 1 mm wall thickness at 1200°C, about 10,000 h,  
for a 0.05 mm wall thickness at 1100°C, about 700 h,  
for a 0.05 mm wall thickness at 1200°C, about 80 h.

Theoretical considerations allow the inference that with  
5 a 100°C temperature increase, the life span decreases by about a  
factor of 10. The  $t_b$  temperature dependence follows from the known  
temperature dependence of the oxide growth rate  $k$ , which is defined  
as follows:

$$k = k_0 e^{-Q/RT}$$

10 where  $Q$  = the activation energy for diffusion processes in the  
layer,  $T$  = temperature, and  $R$  = general gas constant. The  
remaining-life time ( $t_b$ ) dependence of the component wall strength  
( $d$ ) can be stated for most applications approximately like this:

$t_b$  proportional to  $d^3$ .

15 This illustrates the strong reduction of the remaining-life time,  
when component wall strength is reduced. For very thin-walled  
components consisting of the above-mentioned alloys, as are  
present, e.g. in car-catalyst substrates (foil thicknesses 0.02 to  
0.1 mm), in fiber-based gas burners, or filters (fiber diameter  
20 0.015 to 0.1 mm), operating times of a few thousand hours as are  
required in practice are only possible if the operating  
temperatures are kept relatively low, e.g. around 900°C.

However, in this temperature range, especially between  
800 and 950°C, the growth rate ( $k$ ) of the oxide layer  
25 disadvantageously exhibits a distinct variance from the above-  
mentioned temperature dependence. This difference occurs  
especially in the initial stage (e.g. up to approximately 100 h) of

oxidation stress. This variance is due to the fact that at temperatures about 800°C, the  $\alpha$ -Al<sub>2</sub>O<sub>3</sub> formed at high temperatures (at and above 1000°C) (hexagonal structure; corundum lattice) does not occur, whereas metastable Al<sub>2</sub>O<sub>3</sub> modifications, especially  $\theta$ - or  $\gamma$ -Al<sub>2</sub>O<sub>3</sub> do. These oxide modifications are characterized by significantly higher growth rates than has  $\alpha$ -Al<sub>2</sub>O<sub>3</sub>. They generally occur only in the initial stages of oxidation. After long periods, transition to stable  $\alpha$ -Al<sub>2</sub>O<sub>3</sub> with corresponding low growth rates occur.

The life span of a component at 900°C therefore cannot generally be extrapolated from the oxide growth rates known at higher temperatures. For thick-walled components with a wall thickness of 1 to 2 mm, for example, this is generally not a problem, since the aluminum reservoir in the alloy is sufficiently high that the initial high growth rate at temperatures around 900°C, due to the metastable oxide modifications, does not result in a significant reduction of the total aluminum reservoir.

However, for very thin components, e.g. 0.003 to 0.1 mm thin foils, because of the initial high growth rate of the oxide layer, the existing very small aluminum reservoir may be exhausted disadvantageously even within a few hours. This regularly causes complete destruction of the components. The actual life span is therefore less by orders of magnitudes, as could be expected from the extrapolation of the growth rates of the  $\alpha$ -Al<sub>2</sub>O<sub>3</sub> layers at high temperatures (1000 to 1200°C). The above-mentioned alloys are therefore not suitable for application in the afore-mentioned

thin-walled components, e.g. car catalysts, gas burners or filter systems.

#### Object and solution

The object of the invention is to provide a method, whereby aluminum-containing alloys form an oxide cover layer substantially composed of  $\alpha\text{-Al}_2\text{O}_3$  when applying a temperature exceeding  $800^\circ\text{C}$ , especially in the initial phase of oxidation, thereby exhibiting clearly improved long-term behavior.

#### Subject of the invention

Within the scope of the invention, it was found that surface treatment of aluminum-exhibiting alloys based on Fe-Al-, Ni-Al, Ni-Cr-Al and Fe-Cr-Al causes improved long-term stability, when using these alloys at temperatures at which metastable  $\text{Al}_2\text{O}_3$  modifications appear. This surface treatment advantageously causes regular inhibition of the formation of metastable Al-oxides under subsequent operational application at higher temperatures around  $900^\circ\text{C}$ , especially in the temperature range of 800 to  $950^\circ\text{C}$ .

The process according to the invention is based on the fact that the presence of other, i.e. non-aluminum-containing oxides on the surface of an aluminum-containing alloy, or a similar component, promotes the formation of the advantageous  $\alpha\text{-Al}_2\text{O}_3$  at operating temperatures above  $800^\circ\text{C}$ . Thus, the disadvantageous formation of metastable  $\text{Al}_2\text{O}_3$  modifications, such as  $\theta\text{-}$  or  $\gamma\text{-Al}_2\text{O}_3$ , is suppressed, whereby the non-aluminum-containing oxides act on the surface of the alloy as nucleating agents promoting especially the formation of the  $\alpha\text{-Al}_2\text{O}_3$  modification at temperatures above  $800^\circ\text{C}$ . This effect occurs advantageously right at the beginning of

the oxidation of the alloy and at operating temperatures, thus regularly preventing the harmful formation of metastable aluminum oxides from the start.

Useful examples of such oxides acting advantageously on the surface are especially Ni oxides, Fe oxides, Cr oxides and Ti oxides. The oxides may be deposited on the surfaces of the components consisting of the said metallic, aluminum-containing alloys or also created by various methods.

These include, especially

Direct deposition of the aforesaid oxides on the alloy surface, e.g. through vaporization and condensing, or cathode sputtering.

Direct deposition of a metallic layer consisting of Ti, Cr, Ni or Fe on the surface of an alloy using deposition methods known from prior art. With a high-temperature application of above 800°C, the said metals convert to the desired oxides in an oxygen atmosphere.

Treatment of the alloy in a chloride- and/or fluoride-containing solution, or a gaseous atmosphere, in which such a solution is present. A Fe-, Ni- or Cr-containing oxide or hydroxide thus forms at the surface of the alloy, depending on the alloy base. With a high-temperature application, the hydroxides convert to their corresponding oxides.

A temperature treatment of the alloy, whereby a temperature below 800°C is initially set, [and]

whereby preferably the additional alloy elements {except aluminum} form an oxide layer on the surface.

5 All these methods have in common that initially an oxide layer, which does not substantially consist of an aluminum oxide, forms on the surface of the alloy. Moreover, to get the desired effect of the advantageous formation of an  $\alpha\text{-Al}_2\text{O}_3$  layer, or the inhibition of metastable aluminum-oxide layers, it may be sufficient when the surface layer exhibits further, non-aluminum-  
10 containing oxides with a concentration of at least 20%, and especially above 50%.

By a surface layer of the alloy is meant a near-surface area with a thickness of up to 1000 nm. Within the scope of the invention, it has emerged that the action of the non-aluminum-  
15 containing oxides on the surface of the alloy already occurs with a thickness of the layers of only a few nm.

#### Special specification section

The subject of the invention will be explained in more detail in reference to several examples, without limiting the scope  
20 of the invention.

A schematic representation of the dependence on temperature of the oxide growth on alloys of the Fe-Al, Fe-Cr-Al, Mi-Al or Ni-Cr-Al type is provided in the figure.

25 The dashed lines indicate the thickness of an oxide layer formed on the surface of a corresponding alloy with exclusive formation of  $\alpha\text{-Al}_2\text{O}_3$  at the corresponding temperatures versus time (both in arbitrary units). After an initial somewhat steeper

gradient of the growth rate, it then remains almost constant causing an almost linear increase of the thickness of the layer over longer periods. Altogether, the formed thickness of the layer increases, when the relevant operating temperature decreases.

5           Moreover, for a temperature of 900°C, indicated by a continuous line, the thickness of the layer at the initial formation of metastable aluminum oxides and subsequent formation of  $\alpha\text{-Al}_2\text{O}_3$  is indicated. The comparison highlights the distinctly higher growth rate of the metastable aluminum oxides, precisely in  
10 the initial stage. During the further process, the growth rate remains almost constant, so that over time, an almost linearly increasing thickness of the layer forms.

As treatment methods for obtaining the advantageous non-aluminum-containing oxides on the surface of aluminum-containing  
15 alloys, the methods described in the following have proven especially effective:

1. A Ni oxide, Fe oxide, Cr oxide or Ti oxide is deposited during vaporization and condensation on the surface of a component consisting of an aluminum-containing alloy with a  
20 preferred thickness of 5 to 1000 nm. This deposition method is thus equivalent to the prior art.

2. On the surface of a component consisting of an aluminum-containing alloy, a metallic layer consisting of Fe, Ni, Cr or Ti is initially deposited to get a thickness of 5 to 1000 nm  
25 by common deposition methods. As suitable deposition methods, especially vaporization and condensing, cathode sputtering, galvanic coating may be mentioned. For operational application,



i.e. at temperatures above 800°C, these metals convert to the corresponding oxides in an oxygen atmosphere.

3. A component consisting of an aluminum-containing alloy is treated in a chloride- and/or fluoride-containing solution, or in a gaseous atmosphere, in which such a solution is present. A suitable solution is, for example, a 10% NaCl solution in water. This treatment is done at room temperature, or at a slightly increased temperature of about 80°C. During this treatment, which is done over a period of a few minutes and up to two hours, a Fe- or Ni-containing oxide and/or hydroxide forms at the surface of the component, depending on the alloy base. With subsequent high-temperature application, the possibly present hydroxide converts to the desired Fe oxide ( $\text{Fe}_2\text{O}_3$ ) or Ni oxide (NiO).

4. A component is initially exposed to a temperature of 750°C for a period of a few minutes up to five hours, whereby a Fe- or Ni-containing oxide forms on the surface depending on the alloy base.